Impact of Submerged Aquatic Vegetation on Radiative Transfer and Hyperspectral Remote Sensing in Optically Shallow Waters: Continued Analysis of CoBOP Data

Richard C. Zimmerman
Department of Ocean, Earth & Atmospheric Sciences
Old Dominion University
4600 Elkhorn Ave
Norfolk, VA , 23529

Grant Number: N00014-97-10032

LONG-TERM GOALS

The goals of this study are to develop models of radiative transfer for optically shallow waters with benthic substrates colonized by submerged aquatic vegetation (SAV). The models will enable prediction of upward spectral radiation from the seafloor, thereby permitting (i) the use of optical remote sensing to retrieve bathymetry, (ii) the search for submerged objects of anthropogenic origin and (iii) the mapping of submarine resource distribution and abundance in coastal waters. These models will also have important applications for predicting irradiance levels within submerged plant canopies, leading to better understanding of light requirements and primary productivity of these important resources.

OBJECTIVES

Specific objectives of this study were to:

- Develop radiative transfer models of seagrass and seaweed canopies *in situ* that account for canopy architecture, impacts of water motion and bottom reflectance from the canopy/substrate complex,
- Use the resulting models of bottom reflectance to develop hyperspectral remote sensing algorithms of SAV composition, abundance and depth distribution, and
- Evaluate the utility of the remote sensing algorithms to retrieve bottom reflectances in both extremely clear oligotrophic waters and in more turbid waters characteristic of eutrophic temperate coastal and estuarine environments.

APPROACH

The work involved development of mathematical descriptions of canopy architecture, reflected upwelling irradiance, light absorption and photosynthesis from direct field observations and laboratory measurements. A system of coupled equations generated from these measurements were solved for specific scenarios of canopy structure and water column optical properties to evaluate the effects of spectral light quality and intensity of the downwelling irradiance on spectral reflectance from the seafloor boundary and whole canopy production. Model predictions of benthic reflectance and water-leaving radiance were tested against *in situ* measurements to assess the degree of closure achieved between theory and observation.

Report Documentation Page						*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE **30 SEP 2003**		2. REPORT TYPE				3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Impact of Submerged Aquatic Vegetation on Radiative Transfer and Hyperspectral Remote Sensing in Optically Shallow Waters: Continued Analysis of CoBOP Data**						5a. CONTRACT NUMBER
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)						5d. PROJECT NUMBER
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Ocean, Earth & Atmospheric Sciences,,Old Dominion University,4600 Elkhorn Ave,,Norfolk,,VA, 23529**						8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)						10. SPONSOR/MONITOR’S ACRONYM(S)
						11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT **The goals of this study are to develop models of radiative transfer for optically shallow waters with benthic substrates colonized by submerged aquatic vegetation (SAV). The models will enable prediction of upward spectral radiation from the seafloor, thereby permitting (i) the use of optical remote sensing to retrieve bathymetry, (ii) the search for submerged objects of anthropogenic origin and (iii) the mapping of submarine resource distribution and abundance in coastal waters. These models will also have important applications for predicting irradiance levels within submerged plant canopies, leading to better understanding of light requirements and primary productivity of these important resources.**						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**		

WORK COMPLETED

In the first year, canopy architecture for the eelgrass meadow growing at Del Monte Beach, Monterey, California was characterized. A model of vertical canopy architecture wad developed and expanded in Years 2-4 to include the effects of flow on canopy architecture and spectral distribution of irradiance within the canopy in Monterey Bay, California and Lee Stocking Island, Bahamas. Years 3 and 4 continued to evaluate inherent optical properties of individual submerged plants for the canopy model, measurement of bottom reflectance over submerged plant canopies using the Diver-Operated Benthic Bio-Optical Spectrometer (DOBBS) and measurements of remote sensing reflectance over submerged plant canopies using a hyperspectral tethered spectroradiometer buoy (HTSRB). Year 5 focused on refinement of the optical model to include the effects of light scattering by the canopy and water column and further development of remote sensing algorithms for bathymetry retrieval and vegetation mapping with hyperspectral remote sensing datasets. Data files consisting of inherent optical properties (*a*, *b* and *c*) properties measured around the Monterey Peninsula, CA USA using a Shimadzu UV2101 spectrophotometer were deposited in the World Ocean Optics Database (WOOD) in September 2001. Years 6 and 7 were spent completing the data analysis and preparing manuscripts for publication. As of this writing, six papers have been published, two book chapters are in press, one manuscript is in review and three papers are in prep.

RESULTS

ZIMMERMAN, R. 2003. A biooptical model of irradiance distribution and photosynthesis in seagrass canopies. Limnol. Oceanogr. ***48:*** *568-585.* Although extremely vulnerable to coastal eutrophication, seagrasses represent important structuring elements and sources of primary production in shallow waters. They also generate an optical signature that can be tracked remotely. Accurate knowledge of light absorption and scattering by submerged plant canopies permits the calculation of important plant- and ecosystem-level properties, including rates of photosynthesis, vegetation abundance and distribution. The objectives of this study were to develop a realistic, yet simply parameterized two-flow model of plane irradiance distribution through a seagrass canopy submerged in an optically active water column, to evaluate its performance against in situ measurements and to explore the impacts of variations in canopy architecture on irradiance distribution and photosynthesis within the canopy. Allometric functions derived from leaf length-frequency data enabled simple parameterization of canopy architecture. Model predictions of downwelling spectral irradiance distributions in seagrass canopies growing in both oligotrophic and eutrophic waters were within 15% of field measurements. Thus, the model provides a robust tool for investigating photosynthetic performance of seagrass canopies as functions of water quality, depth distribution, canopy architecture and leaf orientation. Model predictions of upwelling irradiance were less reliable, particularly in the upper half of the canopies. The model was more sensitive to leaf orientation than leaf optical properties, seabed reflectance or the average cosine of downwelling irradiance. Better knowledge of leaf orientation appears to be a fruitful avenue for improving our understanding of the interaction between seagrasses and the submarine light environment.

DIERSSEN, H., R. ZIMMERMAN, R. LEATHERS, T. DOWNES, and C. DAVIS. 2003. Remote sensing of seagrass and bathymetry in the Bahamas banks using high resolution airborne imagery. Limnol. Oceangr. ***48:*** *444-455.* New coastal ocean remote sensing techniques permit benthic habitats to be explored with higher resolution than ever before. A mechanistic radiative transfer approach is developed that first removes the distorting influence of the water column on the remotely sensed signal to retrieve an estimate of the reflectance at the seafloor. The retrieved bottom reflectance is then used

to classify the benthos. This spectrally-based approach is advantageous because model components are separate and can be evaluated and modified individually for different environments. Here, we applied our approach to quantitatively estimate shallow-water bathymetry and leaf-area index (LAI) of the seagrass Thalassia testudinum for a study site located near Lee Stocking Island, Bahamas. Two high resolution images were obtained from the Ocean Portable Hyperspectral Imager for Low-Light Spectroscopy (Ocean PHILLS) over the study site in May 1999 and 2000. A combination of in situ observations of seafloor reflectance and radiative transfer modeling were used to develop and test our algorithm. Bathymetry was mapped to meter scale resolution using a site-specific relationship (r^2=0.97) derived from spectral ratios of remote sensing reflectance at 555 and 670 nm. Depth-independent bottom reflectance was retrieved from remote sensing reflectance using bathymetry and tables of modeled water column attenuation coefficients. The magnitude of retrieved bottom reflectance was highly correlated to seagrass LAI measured from diver-surveys at seven stations within the image (r^2=0.88-0.98). Mapped turtlegrass LAI was remarkably stable over a 2-year period at our study site, even though Hurricane Floyd swept over the study site in September 1999.

DRAKE, L., F. DOBBS, and R. ZIMMERMAN. 2003. Effects of epiphyte load on optical properties and photosynthetic potential of the seagrasses Thalassia testudinum Koenig and Zostera marina L. Limnol. Oceanogr. ***48:*** *456-463.* The biomass and optical properties of seagrass leaf epiphytes were measured to evaluate their potential impact on the photosynthetic performance of the seagrasses Thalassia testudinum Banks ex König (turtlegrass) and Zostera marina L. (eelgrass). Turtlegrass was obtained from oligotrophic waters near Lee Stocking Island, Bahamas; eelgrass was collected from a eutrophic environment in Monterey Bay, California. Leaf epiphyte loads were characterized visually and quantified using measurements of their phospholipid biomass. Light absorption and backscattering of the intact epiphyte layer were determined spectrophotometrically. Turtlegrass epiphytes from the oligotrophic site absorbed a maximum of 36% of incident light in peak chlorophyll absorption bands, whereas higher epiphyte loads on eelgrass from the more eutrophic Monterey Bay absorbed 60% of incident light in peak chlorophyll absorption bands. The combination of intact epiphyte-leaf complexes and spectral measurements enabled us to construct a quantitative relationship between epiphyte biomass and light attenuation, and, by extension, between epiphyte biomass and seagrass photosynthesis. The model yielded a robust, positive relationship between epiphyte biomass and the absorption of photons in photosynthetically important wavelengths, and it generated a strong negative relationship between epiphyte biomass and spectral photosynthesis of their seagrass hosts. Furthermore, the calculations of photosynthesis highlighted the significant differences between PAR and spectral models of photosynthesis, illustrating that the spectral quality of the incident flux must be considered when evaluating the effects of epiphyte load on seagrass leaf photosynthesis. Verification of the model—using direct measurements of photosynthesis and a variety of epiphyte and macrophyte combinations from different locations—is warranted.

CUMMINGS, M., and R. ZIMMERMAN. 2003. Light harvesting and the package effect in Thalassia testudinum Koenig and Zostera marina L.: Optical constraints on photoacclimation. Aquat. Bot. 75: 261-274.. Although seagrasses possess numerous adaptations for life underwater, they lack the specialized accessory pigments for the efficient harvesting of green light that dominates many aquatic environments. Without these specialized pigments, photoacclimation by seagrasses is likely to result in a severe package effect, i. e., the loss of linearity between light harvesting efficiency and pigment loading. Here we investigated the optical constraints imposed by the package effect on photoacclimation in seagrass leaves. Pigment concentrations and leaf optical properties (absorptances, absorption coefficients and optical cross sections) of turtlegrass (*Thalassia testudium*) leaves from Lee Stocking Island (Bahamas) and eelgrass (*Zostera marina*) leaves from Monterey Bay, California,

U.S.A. were measured at different times of the year. Chlorophyll concentrations and optical cross sections differed by a factor of five across sampling dates and populations. Increases in leaf-specific absorption among seagrass leaves were greatest in the green (500 to 600 nm), while the package effect, as measured by a decrease in leaf optical cross section, was most severe in the blue (400 to 500 nm) and red (600 to 700 nm). Consequently, the five-fold range in pigment concentration resulted in similar photosynthetic light harvest efficiencies ($\phi_L \approx 50\%$ of incident PAR) for intact seagrass leaves in their native light environments. Although the package effect has significant impacts on the optical properties of seagrass leaves, chlorophyll use efficiency does not appear to play a strong role in the ecology or evolution of seagrasses.

BURDIGE, D., and R. ZIMMERMAN. 2002. Impact of seagrass density on carbonate dissolution in Bahamian sediments. Limnol. Oceanogr. ***47:*** *1751-1763.* Carbonate dissolution has been widely observed in shallow water tropical sediments. However, sediment budgets have generally not been closed with respect to the amount of acid production required to produce the observed carbonate dissolution. Recently it has been suggested that enhanced oxygen transport into sediments through the roots and rhizomes of seagrasses might play a role in resolving this mass balance problem. We conducted studies of seagrass-carbonate sediment interactions in shallow water sediments around Lee Stocking Island, Exuma Islands, Bahamas to further examine this problem. Our studies showed that alkalinity and .CO2 increased with depth in the pore waters, while pH and calculated carbonate ion concentration decreased with depth. All of these observations are consistent with the occurrence of carbonate dissolution in these sediments. The magnitude of pore water alkalinity and .CO2 changes were also related to seagrass density, with the largest gradients seen in the sediments of dense grass beds. Calculations suggest that less than ~50% of the O2 needed to drive aerobic respiration (and ultimately carbonate dissolution via CO2 production) can be supplied by transport processes such as diffusion, bioturbation and physical pore water advection. Furthermore, the O2 needed to balance the carbonate dissolution budget could be provided by the transport of <15% of the photosynthetically derived O2 to the sediments through seagrass roots and rhizomes without enhancing the removal of carbonate dissolution end-products. Thus seagrasses play an important role in controlling the rates of carbonate dissolution in shallow water tropical marine sediments.

FUCHS, E., R. ZIMMERMAN, and J. JAFFE. 2002. The effect of elevated levels of phaeophytin in natural waters on variable fluorescence mreasured from phytoplankton. J. Plank. Res. ***24:*** *1221-1229***.** Variable fluorescence methods are becoming popular in studies related to aquatic photosynthesis. In natural ocean water, phytoplankton coexist with their zooplankton and flagellate predators, viral parasites and the waste product of digested phytoplankton cells that contain phaeophytin (a chromophore, produced by digestion of chlorophyll *a*). Fast Repetition Rate Fluorometery, a technique mainly applied in phytoplankton studies, was used to evaluate and quantify the effect of phaeophytin abundance in seawater on variable fluorescence parameters: the photochemical quantum yield, F*F* (also known as *Fv/Fm*) and the functional cross section of Photosystem 2 (PS2), s*PS2*. If F*F* is determined lower than what it actually is, phytoplankton may be labeled as less healthy (or productive) than their true condition. Results were compared with data collected using another widely used variable fluorescence technique, the 'pulse amplitude modulation' (PAM). Our study concludes that for significantly elevated levels of phaeophytin in the water, the measured values of F*F* should be corrected to avoid misinterpretation. This conclusion is irrelevant of the measuring instrument. In waters with phaeophytin levels that constitute less than ~30% of the total measured pigment, no correction is required (less than 5% change in F*F* is expected). However, as phaeophytin levels rise, the effect on F*F* increases and becomes more significant (e.g. F*F* appears 25% lower when the

phaeophytin to total pigment ratio is ~70%). High concentrations of phaeophytin are not often reported in the open ocean. However, in highly productive coastal waters high levels of phaeophytin can be encountered. The functional cross section (s*PS2*) measurements are not affected by the presence of phaeophytin in the water.

IMPACT/APPLICATIONS

The computation of radiant energy distributions in plant canopies permits the calculation of (i) photosynthesis rates important for ecosystem and biogeochemical studies, and (ii) reflectance parameters required for remote sensing evaluation that can be used for seafloor characterization, object identification and resource mapping in optically shallow waters. The studies undertaken here have led to the development of a useful model for radiative transfer calculations in submerged plant canopies and algorithms for the retrieval of bathymetry and vegetation parameters (vegetation type and density) from hyperspectral R_{rs} imagery.

TRANSITIONS

All data are being prepared for transfer to the CoBOP database for archival and use by others. Ten data sets consisting of water column optical property observations of nearshore waters in Monterey Bay were transferred to J. Smart (APL, Johns Hopkins Univ) for the World Ocean Optics Database (WOOD). This project has also provided data sets to C. Davis, F. Dobbs, D. Burdige, R. Maffione, C. Mobley, W. Philpot, and P. Reid as part of various CoBOP-related collaborations. The seagrass bio-optical model has attracted considerable interest from seagrass management agencies and other scientists interested in coastal water quality and resource monitoring (see **RELATED PROJECTS**).

RELATED PROJECTS

In addition to the CoBOP collaborations described above, the seagrass bio-optical model is being utilized by the Washington State Department of Natural Resources to map potential seagrass habitat throughout Puget Sound. The seagrass bio-optical model is also being used to evaluate an ecoengineering scheme to enhance circulation and benthic productivity of shallow embayments along the coast of Japan. This work is funded by a grant awarded the New Energy Development Organization (NEDO) of Japan. We are examining the capacity for enhancing seagrass productivity through the fertilization of these severely CO_2-limited plants (Zimmerman et al. 1995; Zimmerman et al. 1997) with industrial flue gas generated by fossil-fuel burning electric power plants. The model is being used to predict light requirements, potential distributions and densities of seagrasses in these turbid, light-limited environments as a function of flow and degree of CO_2 enrichment.

A three-year NSF award was received in 2002 to further explore the biogeochemical consequences of seagrass productivity in shallow carbonate systems, in collaboration with D. Burdige at Old Dominion University. The objective of this project will be to relate large scale patterns of seagrass distribution obtained from remote sensing platforms to rates of carbonate sediment dissolution on the Bahamas Bank and evaluate their impacts on the global carbon cycle.

REFERENCES

Zimmerman, R., D. Kohrs, D. Steller and R. Alberte. 1997. Impacts of CO_2 -enrichment on productivity and light requirements of eelgrass. Plant Physiol., 115: 599-607.

Zimmerman, R. C., D. G. Kohrs, D. L. Steller and R. Alberte. 1995. Sucrose partitioning in *Zostera marina* L. in relation to photosynthesis and the daily light-dark cycle. Plant Physiol., 108: 1665-1671.

PUBLICATIONS

Van Duin, E., G. Bloom, F. J. Los, R. Maffione, R. Zimmerman *et al.*, 2001 Modeling underwater light climate in relation to sedimentation, resuspension, water quality and autotrophic growth. Hydrobiolgia 44: 25-42. [published, referred]

Burdige, D., and R. Zimmerman. 2002. Impact of seagrass density on carbonate dissolution in Bahamian sediments. Limnol. Oceanogr. **47:** 1751-1763. [published, referred]

Fuchs, E., R. Zimmerman, and J. Jaffe. 2002. The effect of elevated levels of phaeophytin in natural waters on variable fluorescence mreasured from phytoplankton. J. Plank. Res. **24:** 1221-1229. [published, referred]

Cummings, M., and R. Zimmerman. 2003. Light harvesting and the package effect in *Thalassia testudinum* Koenig and *Zostera marina* L.: Optical constraints on photoacclimation. Aquat. Bot. **75:** 261-274. [published, referred]

Dierssen, H., R. Zimmerman, R. Leathers, T. Downes, and C. Davis. 2003. Remote sensing of seagrass and bathymetry in the Bahamas banks using high resolution airborne imagery. Limnol. Oceangr. 48: 444-455. [published, referred]

Zimmerman, R.C. 2003. A bio-optical model of irradiance distribution and photosynthesis in seagrass canopies. Limnol. Oceanogr. 48: 568-585. [published, referred]

Zimmerman, R.C. and A.G. Dekker. In press. Chapter 12: Light in water: how it affects seagrasses and makes them measurable from space, p. 1-25 In A.J. Larkum, C. Duarte and R. Orth (eds). A Treatise on Seagrass Biology. CRC Press. [in press, referred]

Zimmerman, R. In Press. Light and photosynthesis in seagrass meadows, p. 1-25. In A. Larkum, C. Duarte and R. Orth [eds.], A Treatise on Seagrass Biology. CRC Press. [in press, referred]

Dierssen, H., and R. Zimmerman. In review. Benthic ecology from space: Seagrass primary production over the Bahamas Banks. Limnol. Oceanogr. [submitted, referred]